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Review Article

IT-Enabled Integration of Renewables: A Concept for the Smart Power Grid

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The wide utilisation of information and communication technologies is hoped to enable a more efficient and sustainable operation of electric power grids. This paper analyses the benefits of smart power grids for the integration of renewable energy resources into the existing grid infrastructure. Therefore, the concept of a smart power grid is analysed, and it is shown that it covers more than for example, time-of-use energy tariffs. Further, the communication technologies used for smart grids are discussed, and the challenge of interoperability between the smart grid itself and its active contributors such as functional buildings is shown. A significant share of electrical energy demand is and will be constituted by large functional buildings that are mostly equipped with automation systems and therefore enable a relatively simple IT integration into smart grids. This large potential of thermal storages and flexible consumption processes might be a future key to match demand and supply under the presence of a high share of fluctuating generation from renewables.

1. Introduction

Strong drivers are working towards more information and communication technology in the power grids. On the electrical engineering side, efficient components and generation from renewable energy resources are the most important ones. On the IT side, the introduction of an automation infrastructure, so to say a "fieldbus for energy grids", is of high importance. Of course, information technology is not an end in itself in this context, but a means for more efficient, sustainable, and cost-effective provision of electrical energy and ancillary (i.e., supporting) services. The vision of the future power grid with an increased level in utilization of information technology is that of a "smart grid". The term "smart grid" or "smart electricity grid" is promoted by the European technology platform of the same name, which is formed by many stakeholders in this area. Similar activities are ongoing in the US and Japan (see http://www.smartgrids.eu/, visited 12/2008).

The key difference between the state-of-the-art power grids and future smart grids is that the latter will strongly rely on information and communication technology, which enables a seamless coordination of all grid components, such as large and small generators, the transmission and distribution grid itself, energy consumers, and even storages. By means of such a seamless coordination, an energy- and cost-efficient grid operation can be realized in a "smart" way.

The purpose of this paper is to analyse the benefits of a smart power grid for the integration of renewable energy resources into the existing grid infrastructure.

Currently, a strong shift from central generation towards a combination of central and distributed generation can be observed [1, 2]. This decentralization leads to greater stresses for the hierarchically structured power infrastructure. There are not only top-to-bottom energy flows, but also traverse energy flows on lower levels that increase the load to not expected levels. Things are even more demanding if integration of renewable energies is envisaged on a larger scale, because the actual generation can vary grossly according to changing weather conditions [3]. In the grid itself, the automation infrastructure will propagate from the (in some countries fully automated) high-voltage-level

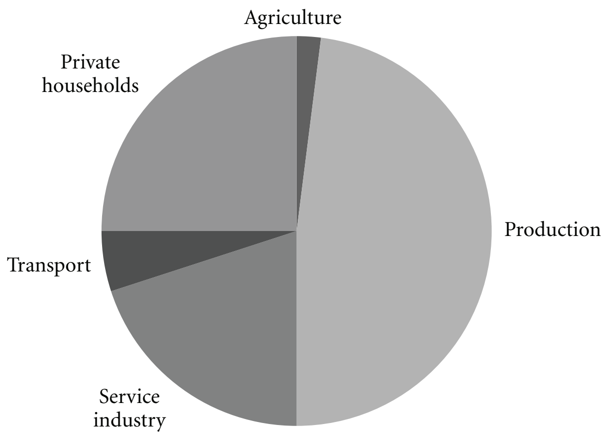

Figure 1: Electricity consumption of Austria 2007. The service industry sector, congruent with energy demand of functional buildings, accounts for 20% of the total demand (207 PJ)(Souce: Statistik Austria, http://www.statistikaustria.at/).

towards the lower levels, namely, medium- and even low-voltage level. It will therefore soon reach the levels where larger energy consumers (industry and large buildings) are connected. This offers the opportunity for energy consumers to cooperate with the electricity grid instead of being passive energy subscribers. Large entities like buildings, for example, can then behave as an "active" participant or a micro grid within the scope of the smart power grid.

A huge potential for flexible energy demand and demand reduction can be found in today's buildings. Functional buildings account for approximately 20% of the total electricity demand in Austria (see Figure 1). In more urbanized countries, this share can be even higher. This potential can be leveraged with building automation systems. The respective communication technology is already widely spread; it would however be necessary to adapt the systems so they can manage the electricity usage in buildings and to integrate them into the smart grid communication infrastructure. This way, buildings can become active electricity consumers that not only use energy but also optimize and regulate the whole electricity and energy balance.

The rest of paper is organised as follows: Section 2 analyses the different motivations for the deployment of smart power grids. The different applications that make out such a smart grid are discussed in Section 3. Section 4 analyses the state of the art in communication technologies used in the power grid and points out open issues. Before giving conclusions in Section 6, Section 5 covers the role of large functional buildings as active participants in a future smart power grid.

2. Motivations for Smart Power Grids

The central motivations behind smart power grids are the need to reduce CO_2 emissions, the integration of renewable energy resources into the existing grid infrastructure, and the growing pressure to use the power grid more to its limits.

Climate protection urges for less energy consumption. For the electrical power system, this means to move from a yearly increase of consumption (e.g., 2% in central Europe) to a decrease. Energy efficiency measures on demand and supply side are necessary. Smart grids, that is, the application of communication technology, can help here by enabling better customer information, automated detection of unnecessary energy uses, and distributed optimisation of consumption processes.

For a sustainable and secure future electrical energy provision, it is inevitable to significantly increase the share of generation from renewable sources in the energy system. Compared to the traditional generation from fossil resources, the energy density of renewable energy sources is low. The number of generation units is comparably high, but they have a rather low individual power output compared to large centralised power plants. The integration of such distributed generators into the existing power grids leads to a number of different issues [4]. One of these issues is the fact that a strong growth of electricity generation in the medium-voltage grid, where most of the installed distributed generation injects its power, leads to grid voltage problems [5]. At the feed-in points, the grid voltages reach the given limits in times of low demand, so that no more units can be installed without significant grid investments [6, 7]. Here, online voltage control in the medium-voltage feeders (basing on measurement data from critical grid nodes) by controlling grid components such as tab changer transformers and generation units, the so-called active grid operation [8], can solve the problem of keeping the grid voltage in the defined limits. Instead of investing into new power lines, the problem is tackled by installing comparably inexpensive communication systems and controllers [9].

It can be expected that energy systems will in future be operated closer to their limits as it is currently the case. One of the reasons for that is that the pattern and kind of investments into the grid infrastructure will change due to the liberalisation of power markets. For maintaining the high standards in power quality, it is already today considered to be necessary to monitor power quality variables such as voltage, flicker, and harmonics using on-line measurements in the grid. In order to avoid future system blackouts, it is necessary to have reliable real-time grid data and coordinated automated controls available to be able to take immediate action against system events to prevent cascading [10].

Taking all these driving factors together, it is foreseeable that information from the grid will become more than any conventional SCADA (supervisory control and data acquisition) system can currently handle. For tackling this emerging complexity, it is necessary that the information handling is done in a much more decentralised manner than it is done today. The development from large and bulky centralised systems to lightweight distributed solutions can also be seen in other areas. Even in such a safety-critical application area as aircraft control, information technology and communication systems are common today [11]. This example shows that it is possible to design highly dependable and fault-tolerant control systems, which ultimately improve the safety of the application system (here: aircraft) instead of having a negative influence on dependability. The fear that information and communication technology will have negative impact on the dependability of the power grid as a whole is still common among grid operators today. It mainly originates from the false impression that the level of dependability achievable by modern information systems is equal to the dependability we experience from consumer products on a daily basis. Nevertheless, it cannot be neglected that the inclusion of communication technology into the power infrastructure will make the operation more complex due to various issues like security, scalability, availability, and others.

In various regions of the world, a different focus is put on the discussed motivations for smart grids. Some countries are primarily dealing with the integration of renewables, whereas others need to improve the security of supply. However, the smart grid approach is not intended to cure isolated problems. It offers a solution to a bundle of power grid challenges that relies on the synergies made available by an integral communication infrastructure.

3. The Role of Communications in Smart Power Grids

The ability of communication (and therefore coordination) between grid components can be seen as the defining aspect of smart grids in contrast to conventional power grids. Therefore, communications play a major role. As outlined in Section 2, the primary reason why communications are needed is the more decentralised structure of power grids that results from a wide application of renewable energy resources. Conventional communication strategies in the grid, such as power-frequency control, are designed for a low number of active nodes (adjustable generators) in the grid [12]. More distributed systems require a higher level of coordination in order to maintain stability [13]. However, not only power balancing requires communication. Besides today's Supervisory Control and Data Acquisition (SCADA), there are three major application domains for communications in smart grids.

3.1. Active Distribution Grids. To allow the integration of a high density of distributed generation in existing medium-voltage infrastructure, an active control of generation power on the basis of voltage or power flow measurements can be utilised at critical points in the grid. One of the main barriers for connecting new generators to the grid is that power feed-in increases the grid voltage at the feed-in point. This is in particular the case in sparsely populated areas, where the grid is not very strong, but a considerable amount of renewable energy resources is available. The line voltage has to be kept in an allowed band (e.g., +/− 10% of nominal value) by the grid operator in any case. The worst case occurs when there is no load but strong energy generation on the feeder.

In an *active* distribution grid, the generation of the distributed generators is managed according to the voltage at critical points. If the voltage rises too high, reactive power management is performed. This is done based on voltage measurements. If this is not effective enough, even the active power can be curtailed [6]. The selection of generator to be curtailed can be done technically, but also economically (price balancing). Such an active management of generated power in a medium- or low-voltage feeder is basically a form of multiobjective control. The challenge here is that sensors, controllers, and actuators are very far from each other. Voltage and power information has to be communicated over dozens of miles once every six seconds or so. The automation infrastructure used has to be highly reliable. Often, the protocols are transported over a variety of different media, depending on the available communication links. For a wide application of such approaches, a common information model for generators and other systems that are part of this control is required (see, e.g., [14]).

3.2. Smart Meters. Smart meters can be part of a smart grid, but they are not the same as smart grids. Although the origins of smart metering technology lies in remote meter reading, many other aspects play a role for smart meter deployment than an automated approach to track consumed kWh. Smart meters are primarily though to inform the energy consumer about his/her consumption and the current electricity tariff. According to economic principles, only with this information the end user becomes a rationally acting market participant and the market-driven optimisation of the energy system can work. Besides the need to track down electricity theft in some countries, the implementation of this principle is the key driver of smart meter deployment at many places of the world.

While in some countries smart meters are area-wide deployed, in other countries the debate about their benefits is still underway. On the positive side, these systems simplify the accounting, and consumers can be promptly informed about their energy consumption. More data is available from the grid, and network development planning can be done on the basis of real data instead of worst case models. Failure detection becomes easier and voltage bands can be used more efficiently. On the negative side, the costs are very high, and it is basically assumed that the consumer will pay the price. Further, there is a severe lack of standards. Long-term reliability and data security questions are not yet completely answered.

From a technical point of view, smart metering systems can be enabled to feature more than consumer information and remote meter reading. Smart metering systems can generate snapshots of the consumption state of the whole grid so that grid operators can examine in detail how much power was flowing to where in the moment of the snapshot. Further, it is possible to measure real consumption profiles, perform on-line power quality monitoring and even remote switching of loads.

Smart meters are interconnected by means of communication links, usually narrowband power line communication to data concentrators at the transformer stations. From here, backbone networks (e.g., glass fibre) bring the data to control centres. Existing communication infrastructures are an essential precondition of smart metering systems, but in many grids they are still nonexistent.

3.3. Automated Demand Response. One of the greatest challenges for a broad utilisation of renewables is to maintain the power balance under the presence of highly fluctuating load *and* generation. Basically, there are three options to solve this problem: conventional backup, energy storage and automated demand response. Today, the most widely used solution is conventional backup, where a drop of generation from renewable is replaced by powering up fast (but inefficient) conventional plants. However, with a rising share of renewables in the system, this option gets more and more inadequate. An alternative in future can be a wider utilisation of storages (even batteries of electric vehicles) in combination with control actions on the demand side [15].

There are several different possible ways of interfering with the operation of electrical loads (see, e.g., [16]). The simplest form is load shedding. The main goal in load shedding (or curtailment) is to cut or reduce loads in critical grid situations without consideration of the user process functionality. Load shedding that is motivated by grid stabilization is usually interfering with customer interests and can only be applied in emergency situations. A minor group of loads, such as lighting in unoccupied rooms, and so forth. can also be curtailed without loss of user comfort. However, in the context of sustainable energy usage, these loads should be switched off in general rather than be used in demand response operations. Modern demand response has to undertake its measures without noticeable changes in the performance of user processes. Therefore, load shifting is the preferred option of intervening with load operations.

Since they are seen as a supporting tool to match supply and demand under the condition of supply from fluctuating renewable energy resources, control measures on the demand side of the power grid play a key role in most "smart grid" visions. Of course, it also makes sense to adjust the generation to the supply by featuring generation technologies where this is possible, for example, for residential combined heat and power (CHP) systems.

Based on their specific processing, properties, and energy storage functionality, there is the possibility to reschedule energy consumption of certain loads. Energy can either be stored in real energy storages, such as thermal storages, or as conceptual energy storages that can be exploited by rescheduling a process to a later point in time (load shift) [17]. Load shifting can be performed in various processes, for example, washing, cleaning, heating, chilling, and pumping. These electricity-consuming processes have, depending on the application, certain degrees of freedom in their time schedule. Each potential flexible load has a certain individual capability that it can commit to the overall system. This capability has usually two dimensions: energy and time. The consumption of certain portion of energy can be pre- or postponed for a certain time. The method can be used for peak reduction, but also for other options such as the provision of short-term balance energy. Load shifting does not aim to reduce energy consumption in long-term, but to reduce peak loads by shifting consumption to off-peak times (see Figure 2) or to adjust it to volatile generation patterns. This can be achieved either with a human-in-the-loop approach (e.g., time-of-use tariffs), where the energy customer gets

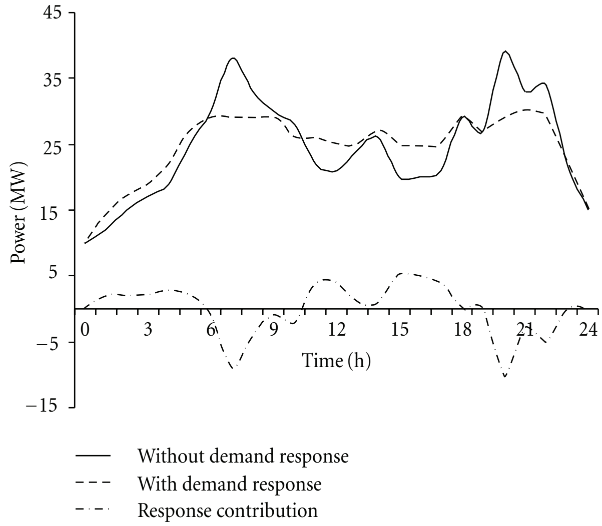

FIGURE 2: Example for automated demand response operation. Power peaks are avoided by consuming less power in peak times and more in off-peak times (load shifting). The DSM contribution is that of a (partly virtual) energy buffering, that is charged in off-peak times and discharged in peak times.

incentives to shift consumption herself/himself, or it can be done in an automated fashion, where the customer is out of the loop.

4. Communication Technologies

Communication between nodes in smart grids can be based on a number of services and technologies. Traditionally, there has been a variety of communication protocols developed for very specific application areas in grid control, such as substation automation, metering, billing, or supervision and control (SCADA). All these application domains have specific requirements, and the (in many cases standardized) solutions were tailored to meet these needs. Metering protocols like IEC 62056 (IEC 1107) or EN 1434-3 (M-Bus) were mostly designed for simple point-to-point readout of electronic meters. Substation automation and SCADA solutions, such as UCA (based on IEC 61850 and IEC 60870) and DNP have stringent real-time requirements. Therefore, they mostly rely on wired and often small-range networks.

The aforementioned application domains are so far rather isolated functional blocks within grid operation. For a smart grid, the challenge is to integrate them into a comprehensive system and to achieve global communication throughout the grid. One of the practical problems is that existing legacy equipment must be reused, which prevents the simple introduction of entirely new solutions. From a high-level information viewpoint, data models can be converted between the individual subsystems to a certain extent. On the pure communication side, such gateway approaches are possible as well, but not always reasonable [18].

One promising starting point for network integration is that many (albeit not all) of the today existing application protocols in power grids support TCP/IP as a transport mechanism. This means that the Internet technology could be the common denominator for a harmonized communication infrastructure, and the question is to find network technologies supporting IP. On the high-voltage level of the grid, fiber-optical networks are already commonly used today. These networks connect primary substations, large power plants, and (centralized) control rooms. They are mostly based on LAN technology and thus not particularly problematic—except for advanced real-time requirements that cannot be easily supported by standard LANs.

The particular challenge for communication in smart grids lies in the medium- and low-voltage levels which are typically not yet included in existing SCADA networks. These lower network levels are characterized by large node numbers and very distributed topologies. It is evident that dedicated wired networks—beside their obvious benefits—are not affordable due to enormous infrastructure costs. For this reason, standardized communication solutions are attractive, and several possibilities do exist.

First of all, public communication networks can be used. While in the past the grid operators usually tried to cover their communication needs by their own infrastructures, the rise of provider-based (tele-)communication networks made public networks interesting alternatives. Consequently, at least parts of the communication needs were satisfied by GSM, GPRS, or UMTS. After their privatization and due to the high-cost pressure in the telecom field, they were often cheaper as utility-owned communication networks. The increased use of these public networks by diverse groups of users, including private end customers, brought their deficiencies to light: availability, reachability, and independency—crucial demands for every utility which are not necessarily guaranteed in public networks—were the impetus for a rethinking. In the meantime, the trend is again moving towards independence of communication network providers. This means that unless a utility owns a telecom provide, telecom networks is not a preferred option for the bulk of communication needed for smart grids.

An option for the setup of utility-owned communication networks are wireless technologies. Radio links can be installed with relatively small costs, and they can be flexibly adapted to changing needs. It must be noted, however, that the frequency bands used for such systems are not always free and may require licensing. For wireless networks, mostly smallband technologies are being used, since broadband network technologies known from the computer networking field such as WiMAX or WLAN are problematic with respect to range and reachability. For small subnets in microgrids with limited range, such solutions are nevertheless a possibility. Critical grid operation mostly relies on reliable point-to-point links. Currently, trunked radio systems like TETRA are becoming popular, for example, in Germany. As TETRA is limited in bandwidth (7.2 Kbit/s per time slot), it can be assumed to be a substitute for services currently run over GSM/GPRS. Typical applications are data collection, in particular metering (load profile meters and household meters), supervision of transformer stations, or safety-related applications. These areas will further grow, and the trend towards active distributions grids will make data more critical, so that the requirements imposed on wireless communication solutions will grow, too. Currently, there is a new initiative underway to define a new physical layer amendment for the IEEE 802.15 WPAN standard (which is the basis for ZigBee and WirelessHART). The goal of the new IEEE 8020.15.4 g is to provide solutions for the specific problems of smart utility networks, in particular large, geographically diverse networks with minimal infrastructure and a very high number of nodes.

An interesting alternative for the medium- and low-voltage grid levels is power line communication which has achieved large attention particularly in the wake of developments in the field of smart metering. Wireless networks controlled by a utility company are not in the position to reliably reach each meter in each individual household. The power line however represents a dedicated connection and is therefore interesting for the entire communication infrastructure. From a technical viewpoint, three different classes of PLC exist: smallband PLC with low-data rate, narrowband PLC with high data rate, and broadband PLC.

Narrowband PLC with low-data rate uses simple approaches without channel coding or equalizing. These systems are typically known from building automation networks, such as EIB PowerNet for in-house automation in retrofitted installations or LonWorks which has been used also for remote metering. These systems are however not suited for reliable real-time data transmission. More advanced communication methods enable narrowband PLC solutions with high data rates. The frequency range between 10–500 kHz is regulated and intensively used in USA, Japan and Asia. In Europe, their practical use in medium- and low-voltage grids is regulated only in the frequency range below 148.5 kHz in the CENELEC bands A, B, C, and D. Although for these low frequencies conducted emission is very critical, measurements required for certification consider only frequencies above 150 kHz. Therefore, components connected to the power line may produce conducted emission within the frequency bands used for PLC. Measurements on MV lines in the Netherlands have shown such high emission originating from wind power plants. Nevertheless, the CENELEC bands below 148.5 kHz and individual bands above are suitable for PLC solutions in grid automation.

Small- and narrowband PLC exhibits relatively modest data rates. Support of plain IP (and even more TCP/IP) is therefore costly and not necessarily a good option. Nevertheless, more efficient approaches exist to still transport existing application protocols over PLC [18]. For the sake of completeness, it should be noted that broadband PLC was developed and optimized mostly as a solution for the “last mile” for telecommunication services like Internet access and voice-over-IP. IP support would be possible here, but broadband PLC is ill-suited for the transport of metering and control data and does not play a particular role in the considerations of communication solutions for smart grids.

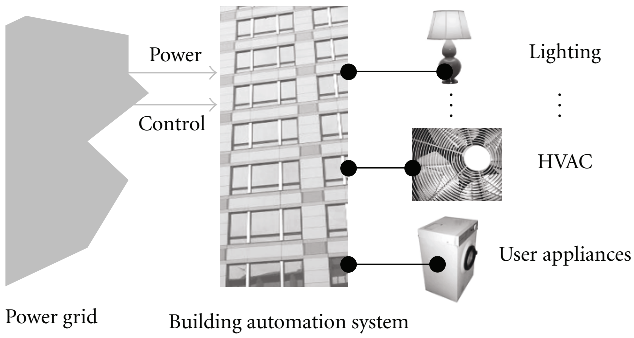

Figure 3: The building as new management layer in the smart grid.

5. Buildings in Smart Power Grids

The roles of the participants in the future smart power grid will not be as easily distinguishable as today. At the moment the power grid consists of a producer and a consumer side, while in the future each node or each part of the grid can act as both. New and flexible nodes come into focus. This type of node wills increase the flexibility of the grid because of their controllability, which is a property the old consuming-only nodes did not have. Buildings, especially big functional buildings with installed building automation systems, are one possibility for such flexible nodes. This would change the view from consuming devices to bigger entities. A building can be seen as a singular node in the whole energy supply system.

Typically, large buildings are connected to different supply systems such as gas, remote heating, and electricity. Within the building, there are dozens of appliances connected to these supply systems. In order to reduce complexity, it is usually moved away from a micromanagement of each single device (see, e.g., [15, 19]) to a higher layer and also abstraction level (see, e.g., [7, 20]) as shown in Figure 3. The approach includes building up objects out of clusters of devices, for example office buildings or groups of houses, and these objects provide demand response functionality by using energy management techniques. Large functional buildings have the advantage that a lot of these buildings have already installed building automation systems, and therefore their interoperation with a smart grid is simpler to realise than connecting each and every single device in the building directly to the smart grid infrastructure.

With this idea in mind, buildings (or appliances in buildings) can propose functionalities for the smart power grid. For example, they can serve as “intelligent loads” or “virtual energy storages” [4]. “Intelligent loads” are electrical loads that can forecast their consumption behaviour for a certain time. The concept of “virtual energy storages” refers to the fact that many electrical loads incorporate (so far nonutilised) energy storage capabilities in the form of thermal or potential energy. The central idea is that providing an infrastructure for distributed energy management and generally intensifying the information flow in the energy system will have positive effects on economic and energetic efficiency of the whole electric energy system [21].

The idea of energy management in buildings is not new.De Almeida and Vine proposed the theoretical structure how an energy management system could be realizable in 1994 [22], but since then no perceivable approaches to establish such systems are visible. Some concepts are traceable, that handle specific problems, for example, peak load avoidance [20]. A significant part of these approaches are based on a communication system between the devices of the system (without considering the building as an organizing entity). For each of these approaches, a new communication infrastructure has to be established which clearly is a drawback because the effort of planning and installing a new communication system could be one motive for not installing such a system in the end.

Building automation systems provide communication between and control of different devices in buildings. Because of the functionality of generating control signals for the devices, it is easily possible to introduce energy management and load control. At the moment, most of these systems are generating these signals out of timetables or the data gathered by occupancy measurement. There is no cause why energetic requirements like the necessity of shifting power could not be the trigger for such a signal.

With the representation of buildings as single objects energy providers only need to build up communication tunnels to the different objects. Through this tunnels control signals of a very abstract type like “peak power avoidance between 12:00 and 2:00 am” can be generated by the providers without the need to know how these signals are converted into real action by the building automation system.

The part of really managing the single devices can be taken over by the different building automation systems. Each type of building automation system could provide an own implementation of the needed functionalities. As big advantage, these implementations can be designed especially regarding the possibilities and advantages each of the system includes. At the moment, at least two different building automation systems exist that are able to support an application for active energy management: BACnet and ZigBee. With these two systems, two very different types of building automation systems already provide mechanisms for this type of management.

For the BACnet approach, the key idea is continuity with very little changes, and so there is only an additional load control object implemented to the existing standard. The BACnet Load Control Object is specified very rudimentary, nevertheless, load shedding of different devices is possible with it [23]. ZigBee on the other hand tries to make step into a totally new direction. The ZigBee document describes a system from protocol level up to different use cases and implementation possibilities for establishing a whole energy measuring and control infrastructure. Together with the feature of being wireless, that is, a clear head start of ZigBee into the world of active energy management and load control [24].

In [25], a more detailed comparison of the implementations is given. It can be summarized that both approaches with all their advantages and drawbacks show that also existing building automation systems can be adapted without big effort for utilizing automated buildings as functional nodes for the future smart power grid.

6. Conclusion

The foremost reason for the power grid having only very few information and communication technologies installed and integrated has been the high costs of such systems in relation to their benefits. The technological advance on the side of information technology, on one hand, and the beginning shortage in energy supply (including the need for CO_2 reduction and thus integration of renewables), on the other hand, result in an economic paradigm shift: as costs for energy rise and costs for communication fall, communication in the power grid becomes affordable. As a result, the grid is facing a substantial growth in the number of controllable nodes (generators, loads, and storages) on one hand and of online sensors for voltage, current, frequency, power, energy, flicker, harmonics, or other data. In the past the grid operator was virtually "blind" on the medium and low voltage level regarding online information of power flows.

This development ultimately can lead to the realisation of "smart" grids, where there is no longer a parallel and isolated operation of different remote metering and control applications but an integrated system basing on a common communication infrastructure that allows a well-coordinated, energy- and cost-efficient grid operation. The key challenge for power grids around the world is or will soon be to accommodate substantial amounts of fluctuating generation from distributed generators. The smart grid concept offers a solution in which the existing grid infrastructure can be used more to its limits. Online feedback from the system gives access to additional reserves resulting from original systematic overdimensioning due to uncertainty of the actual strain.

Further, the large potential of thermal storages and flexible consumption processes might be a future key to match demand and supply under the presence of a high share of renewables. The challenges for this lie especially in the IT integration of active consumers such as functional buildings and their interoperation with the smart grid.

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